SURFACE IMAGING TECHNOLOGIES FOR NASA'S EARTH OBSERVING SYSTEM

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ABSTRACT

The Earth Observing System (EOS) is the major element in NASA's Mission to Planet Earth (MTPE). It will be a 15-year-long mission, employing space-based instrumentation and *in situ* measurements to provide a long-term, contiguous, calibrated and validated data set addressing geophysical and biochemical phenomena occurring in the Earth system. The EOS suite of satellites includes sun-synchronous, polar-orbiting spacecraft with morning or afternoon equator-crossing times. The EOS-AM series, the first of which is slated for launch in June 1998, will address geophysical and biogeochemical processes occurring at or near the Earth's surface; the EOS-PM platforms will address atmospheric phenomena, including the interaction between clouds and radiation. Synergy and complementarity within and between these and other platforms will play a major role in acquiring high-quality data.

We discuss the following instruments: MODIS (Moderate Resolution Imaging Spectroradiometer), ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer), MIMR (Multifrequency Imaging Microwave Radiometer), MISR (Multi-angle Imaging Spectroradiometer), and AIRS/AMSU/MHS (Atmospheric Infrared Sounder/Advanced Microwave Sounding Unit/Microwave Humidity Sounder). Instrument heritage, design, capabilities, and realization are discussed in terms of satisfying scientific requirements. We also discuss the synergy resulting from cross-calibration of the instruments and validation of their resulting data products.

INTRODUCTION AND BACKGROUND

The Earth Observing System (EOS) is the major element in NASA's Mission to Planet Earth (MTPE). EOS is a 15-year mission employing space-based instrumentation and *in situ* measurements to provide a contiguous, calibrated and validated data set addressing geophysical and biochemical phenomena occurring in the Earth system. The EOS suite of satellites includes Sun-synchronous, polar-orbiting spacecraft with morning and afternoon equator-crossing times. The first satellite, EOS-AM1, is scheduled for launch in June 1998. It is designed primarily to address geophysical and biogeochemical processes occurring at or near the Earth's surface, while the PM platform will also take observations principally describing atmospheric phenomena, including the interaction between clouds and radiation. The AM and PM platforms will act in concert with other spacecraft, e.g., AERO (to study stratospheric aerosols), CHEM (atmospheric chemistry), and COLOR (bio-optical observations of the upper 10 m of the ocean), to provide a robust, synergistic, and complementary data set describing the dynamics of the Earth system (see Figure 1). Imaging will play a major role in acquiring data, and several EOS-era instruments will be key players in imaging activities.

[FIGURE 1 ABOUT HERE]

Examples of Imaging Sensors in the EOS Era

The instruments that will be used for imaging purposes all have a long heritage of sensor development. They will benefit from both their heritage and the skills that NASA has developed in planning and implementing such multi-year missions as ERBE (Earth Radiation Budget Experiment), TOMS (Total Ozone Mapping Spectrometer) on Nimbus-7 and Meteor, UARS (Upper Atmosphere Research Satellite), and the production of multi-year data sets for the Earth's atmosphere, oceans, and land, in addition to other missions such as Pioneer, Voyager, Magellan, and Galileo, to name a few. As a result of this long heritage, EOS-era instruments are expected to be reliable, cost-effective, and robust.

Five EOS-era instruments are described: MODIS (Moderate Resolution Imaging

Spectroradiometer), ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer), MIMR (Multifrequency Imaging Microwave Radiometer), MISR (Multi-angle Imaging Spectroradiometer), and a suite of instruments, usually referred to in concert as AIRS/AMSU/MHS (Atmospheric Infrared Sounder/Advanced Microwave Sounding Unit/Microwave Humidity Sounder). Each of the instruments was developed to provide synergy in surface imaging and determining related properties of the atmosphere. Cross-calibration of the instruments and validation of their resulting data products will contribute to this synergy. The instruments' heritage, design, capabilities, and realization are discussed in terms of the mission's comprehensive scientific requirements.

Application of New Imaging Technologies in EOS

EOS instruments are taking advantage of pronounced advances in filter, focal plane, and optical design technology to meet the challenging science requirements imposed by Mission to Planet Earth. Every instrument has its own success story to tell. In the case of MODIS, for example, the instrument has incorporated exciting new methodologies for on-board calibration, including solar-based, lunar-based, and Earth-scene based methods. MODIS also includes the capability for on-board spectral, spatial, and radiometric characterization for the life of the instrument.[1]

MODIS The Quintessential EOS Instrument[2,3]

An excellent example of the development of technologies for EOS-era instrumentation is provided by MODIS (see Figure 2). The instrument initially will allow generation of approximately 45 data products addressing soil, vegetation, and snow characteristics.

[FIGURE 2 ABOUT HERE]

MODIS will concentrate on the measurement of biological and physical processes, with emphasis on the study of ocean primary productivity and biogeochemistry; atmospheric clouds, aerosols and water vapor; and terrestrial land cover, primary production, surface temperature, evapotranspiration and photosynthesis. MODIS is an imaging spectroradiometer, with features relating it to precursor terrestrial, oceanic, and atmospheric instruments: AVHRR (Advanced Very High-Resolution Radiometer), HIRS (High-resolution InfraRed Sounder), the Landsat TM (Thematic Mapper) and Multispectral Scanner (MSS), Nimbus-7 CZCS (Coastal Zone Color Scanner), and SeaWiFS (Sea-viewing Wide Field-of-view Sensor). Over the oceans, MODIS will address sea ice extent, suspended solids, chlorophyll concentration, pigment concentration, and sea-surface temperature. It will also measure cloud and aerosol properties, precipitable water, and atmospheric stability.

Six principle instrument characteristics drove the MODIS design: wide field of view, broad spectral coverage, precise spectral band registration, high radiometric sensitivity, high calibration accuracy, and long life. To meet these requirements, MODIS employs a cross-track scanning mirror and a set of linear detector arrays with spectral interference filters located in four focal planes. MODIS will be mounted on the front of the EOS spacecraft to allow solar calibration and a clear space view for calibration, radiative cooling, and dc restoration. The optical system will provide high throughput and low polarization sensitivity. As shown in Figure 3, it employs a two-mirror, off-axis

[FIGURE 3 ABOUT HERE]

Gregorian telescope with an intermediate field stop for stray light control. Three dichroic beam splitters provide spectral separation, thereby dividing the MODIS spectral domain into the VIS, NIR, SWIR/MWIR, and LWIR regions. Dielectric bandpass filters provide final separation into the 36 spectral bands. Detection is provided by four focal plane assemblies, one for each of the four objective assemblies. Each row of detectors in each spectral band images 10,000 m in the along-track direction during each scan, providing 10 detectors along-track in the 1000-m bands, and 20 and 40 in the 500- and 250-m bands, respectively. MODIS instrument measurement approach parameters are shown in Table 1; accomodation parameters are presented in Table 2.

[TABLES 1 and 2 ABOUT HERE]

One of MODIS' areas of emphasis is reflected in its calibration processes and procedures (see Figure 4). These are

[FIGURE 4 ABOUT HERE]

based primarily on its on-board spectral, spatial, and radiometric sensor calibration using a mix of redundant on-orbit calibrators as well as image- and ground-based calibration techniques. Indeed, given MODIS' role in so many investigations, significant effort is going into pre- and post-launch calibration activities. For example, post-launch calibration involves assessment of total noise, based on dark scenes, black body, space, and night scene analysis. Radiometry is being addressed from the relative (within band and between band) and absolute (radiometric rectification and viewing of specific sites) aspects. Spectral calibration and geometric (spatial) calibration are also being addressed. The use of an on-board spectroradiometric calibration assembly (SRCA) is a major enhancement over heritage instruments. The SRCA provides spectral, radiometric, and spatial calibration. The simple scanning system allows access to calibration sources every scan, with no additional moving parts.

Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER)[4,5]

ASTER is an imaging radiometer being provided for the EOS-AM1 platform by the Japanese Ministry of International Trade and Industry (MITI), to meet the requirements of the ASTER Science Team, an international team of Japanese and American scientists responsible for definition of scientific requirements for the instrument, and the development of algorithms for data reduction and analysis. ASTER (see Figure 5) is the only high spatial resolution

[FIGURE 5 ABOUT HERE]

multispectral imager scheduled to fly on the EOS-AM1 platform. It will provide images of the Earth's surface and clouds. In this, its role is similar to those of MODIS and MISR, which will monitor similar variables globally on a daily basis. ASTER, however, will provide those data on a scale that can directly related to physical processes. The type of data that ASTER will produce globally are now available locally using aircraft instruments. ASTER will use bands in the VNIR, SWIR, and TIR for cloud studies, surface mapping, soil and geologic studies, volcano monitoring, and surface temperature, emissivity, and reflectivity determination. VNIR and SWIR bands will be used for investigation of land use patterns and vegetation, VNIR and TIR combinations for the study of coral reefs and glaciers, and VNIR for digital elevation models (DEMs). TIR channels will be used for study of evapotranspiration, and land and ocean temperature. ASTER will also utilize a stereoscopic imaging capability (see below) to derive local surface DEMs and allow observations of local topography, cloud structure, volcanic plumes, and glacial changes. In addition, ASTER will provide surface radiative temperature, and make use of the multispectral TIR data to derive surface kinetic temperature and spectral emissivity. Such high spatial resolution temperature/emissivity information can be used to verify similar procedures coming from MODIS data. ASTER has its heritage in MESSR, OPS, Landsat TM, and SPOT instrumentation. ASTER will provide simultaneous access to 14 bands, versus 7 in TM and 4 in SPOT. It also provides a larger number of SWIR bands, and provides multispectral thermal emission capability in the 8 to 12 Êm region on a global basis. The VNIR subsystem is based on the MESSR optical sensor flown on Japanese Marine Observation Satellites and the OPS sensor launched on the Japanese Earth Resources Satellite 1. The SWIR subsystem has its heritage in the short-wavelength infrared radiometer also flown on JERS-1. The TIR subsystem, however, is a new development.

The VNIR, SWIR, and TIR subsystems are almost separate instruments, as they have their own optics, filters, detectors and detector cooling, preamplifiers, and inflight calibration. They share power conditioning, image data processing and packetization, command and telemetry handling, and safe mode capability.

The VNIR subsystem is comprised of two independent reflecting-refracting Schmidt design telescope assemblies. The detectors for each of the 14 bands consist of 5000 element silicon CCDs, only 4000 of which are used at any one time. Because of the time lag between the acquisition of the forward-pointing image and the nadir image, earth rotation displaces the image center. The VNIR subsystem is designed to extract the correct 4000 pixels based on the orbital position of the spacecraft.

The SWIR subsystem is based on a single aspheric refracting telescope, using a platinum silicide-silicon Schottky barrier linear array detector for each of the 6 bands. Despite the 8% duty cycle, the cooling apparatus will operate 100% of the time to preclude lost time due to cool-down and stabilization. The 50000 hour life-time requirement of the cryocooler exceeds existing heritage designs, and presents a major design challenge.

The TIR subsystem employs a Newtonian catadioptric telescope with an aspheric primary mirror and lenses for aberration correction. Ten HgCdTe detectors are used for each band.

A summary of ASTER measurement approach parameters is shown in Table 3; accomodation parameters are shown in Table 4.

[TABLES 3 and 4 ABOUT HERE]

ASTER's unique capabilities arise from (1) it being the first simultaneous multispectral spaceborne VIS-NIR-SWIR-TIR high spatial resolution instrument; (2) in-track stereo viewing for digital elevation model generation; and (3) shortwave infrared multi-spectral observation with high spatial resolution. With ASTER, the principal advance comes from the fact that ASTER provides "same orbit" stereo. ASTER multi-spectral and digital elevation data can each be studied independently, but also can be used in a combined manner. Thus, if the scene is free of clouds for the nadir view it will also be free of clouds for the aft view. This also means that wherever the stereo is acquired it will also be clear for the 14 channels of spectral data including the 5 thermal bands.

Multiangle Imaging Spectroradiometer (MISR)[6]

MISR is another instrument scheduled for flight on the EOS AM-1 platform. It has nine

CCD cameras fixed at nine viewing angles out to 70.5°, i.e., four forward of nadir, four aft of nadir, and 1 at nadir (see Figure 6). It is the

[FIGURE 6 ABOUT HERE]

only EOS instrument that will routinely provide multi-angle, continuous coverage of the Earth with high spatial resolution. It will obtain multidirectional observations of each scene within a time scale of minutes, and thereby view each scene under essentially the same atmospheric conditions. Images at each angle will be obtained in four spectral bands centered at 0.443, 0.555, 0.67, and 0.865 μm, thus providing 36 instrument data channels (4 bands for each of 9 cameras). A summary of MIST measurement approach parameters is shown in Table 5; accomodation parameters are shown in Table 6.

[TABLES 5 and 6 ABOUT HERE]

MISR has its heritage in GLL, and Hubble Space Telescope's Wide-field/Planetary Camera (WFPC).

MISR's Global imaging mode will provide continuous planet-wide observations, with most channels operating at moderate resolution and selected channels operating at the highest resolution for cloud screening, image navigation, and stereo photogrammetry. Its Local Mode provides data at the highest resolution in all spectral bands and all cameras for selected 300 × 300 km regions.

MISR will be used to monitor global and regional trends in radiatively important optical properties (i.e., opacity, single scattering albedo, and scattering phase function) of natural and anthropogenic aerosols. Over land, the dependence of absolute radiance and scene contrast as a function of angle will be used to retrieve opacity, absorptivity, and phase function. Over the oceans, the shape of the observed phase functions will provide constraints on the physical properties of the scattering particles. This reliance on angular signatures makes such techniques unavailable to nadir imagers. Aerosol information derived from MISR and radiative transfer algorithms developed as part of the

MISR investigation will also be used to assist in the atmospheric correction of ASTER and MODIS data.

MISR is utilizing high quantum efficiency diodes, which permit a detector-based calibration, thin poly CCDs, to provide enhanced quantum efficiency in the blue region of the spectrum, field-programmable gate arrays, Spectralon-coated solar calibration plate, ion-assisted deposition filters, which allows MISR (and MODIS) to meet stringent science specifications, and yet will provide high durability and stability in orbit for the 5-year+ flight.

Multi-angle radiances obtained by MISR will be classified by scene type, and measured radiances will be directly integrated to yield estimates of reflected flux, and, hence, albedo. Automated stereo image matching algorithms will be used to derive surface topography and cloud elevations from multi-angle stereoscopic observations. Bidirectional reflectance distribution function (BRDF) measurements of various scene types will be used for the development and validation of models relating soil, snow, and ice angular reflectances to surface albedo. For vegetated terrain, measured angular signatures will be related to canopy structural parameters, and will provide improved vegetation cover classifications. This information will be used to derive absorbed photosynthetically active radiation and improved measurements of vegetation canopy photosynthesis and transpiration rates. In contrast to single-view direction images, MISR data will be used to derive a vegetation index based on red and near-infrared fluxes, rather than radiances. The multi-angle observations will also provide information necessary to interpret directional vegetation indices acquired by wide-range angle scanners, such as MODIS.

Multifrequency Imaging Microwave Radiometer (MIMR)[7]

While MODIS, ASTER, and MISR will be flown on the EOS AM1 platform, MIMR (see Figure 7) is scheduled

[FIGURE 7 ABOUT HERE]

for flight on the PM series spacecraft. MIMR is being provided under a Memorandum of Understanding with the European Space Agency (ESA). MIMR is a high-resolution passive microwave spectrometer with heritage in the SSM/I and SMMR instruments, but provides greater frequency diversity, improved spatial resolution, increased swath width, and improved antenna performance. This combination of factors allows complete global coverage in less than 3 days, and provide a 20% greater swath width than available with current passive microwave radiometers. MIMR is slated to measure precipitation rate, cloud water, water vapor, sea surface roughness, sea surface temperature, ice, snow, and soil moisture.

MIMR data will be used in conjunction with data from other EOS instruments. Over land, MIMR observations complement visible, infrared, and active microwave observations of vegetation status, biomass, and soil moisture, important for evaporation and transpiration studies. Over snow- and ice-covered areas, passive microwave data will complement high-resolution data available on surface roughness form synthetic aperture radar, thermal data, and visible multispectral measurements responsive to grain size to support extraction of moisture equivalence. Over oceans, passive microwave data, in conjunction with scatterometer and meteorological sounder data, can be used in studies of heat exchange across the air-sea surface, which are strongly dependent on measurements of sea surface temperature, wind, and atmospheric humidity in the ocean boundary layer. MIMR will provide data on atmospheric water content and precipitation, to be interpreted in combination with Advanced Microwave Sounding Unit (AMSU) and Microwave Humidity Sounder (MHS) data (see below).

A summary of MIMR measurement approach parameters is shown in Table 7; accomodation parameters are shown in Table 8.

[TABLES 7 and 8 ABOUT HERE]

MIMR employs nine feedhorns, yielding 20 available channels. The frequencies were chosen to maximize sensitivity to particular parameters of interest and to operate in protected regions of the spectrum. Channels will be converted to daily spectral maps on a 1° grid; monthly average maps on 1° grids will be produced for precipitation index, sea surface temperature, snow cover parameters, sea ice parameters, atmospheric water vapor burden over oceans, atmospheric cloud water burden over oceans, ocean surface wind stress, and soil moisture index.

Atmospheric Infrared Sounder, Advanced Microwave Sounding Unit, and Microwave Humidity Sounder (AIRS/AMSU/MHS)

Like MIMR, the AIRS/AMSU/MHS suite of instruments are scheduled for flight on the PM series of EOS spacecraft. AIRS/AMSU/MHS together constitute the advanced operational sounding system, a facility instrument program, relative to the High-resolution Infrared Sounder/Microwave Sounding Unit (HIRS/MSU) system that currently operates on NOAA satellites. AIRS is designed to meet the NOAA requirement of a high-resolution infrared sounder to fly on future operational weather satellites. NOAA's AMSU and EUMETSAT's MHS measurements, when combined with AIRS, will be analyzed jointly to filter out the effects of clouds from IR data in order to derive clear-column air temperature profiles and surface temperatures with high vertical resolution and accuracy.

Data obtained from the AIRS/AMSU/MHS instrument complement will improve global modeling efforts, numerical weather prediction, study of the global energy and water cycles, detection of the effects of greenhouse gases, investigation of atmosphere-surface interactions, and monitoring of climate variations and trends. These objectives will be met through improvements in the accuracy of several weather and climate parameters, including atmospheric temperature and water vapor, land and ocean surface temperature, cloud distribution and spectral properties, and outgoing longwave radiation. For land views, AIRS/AMSU will provide skin surface temperature, plus day and night land surface temperature difference. AIRS will provide outgoing day/night longwave surface flux. For oceans, AIRS/AMSU will provide skin surface temperature; AIRS will provide outgoing day/night longwave surface flux. Research data products will include surface spectral emissivity, surface albedo, and net shortwave flux. AIRS has its heritage in HIRS2 and HIS; AMSU and MHS derive from MSU.

AIRS[8]

The AIRS to be flown on EOS-PM1 will replace NOAA's existing operational sounder, the High Resolution Infrared Sounder (HIRS2). HIRS2 provides coverage in 20 spectral bands, covering 3.7 to 15.4 μm with a spectral resolution ($\lambda/\Delta\lambda$) of 50. It is a filter wheel spectrometer with two HgCdTe detectors, cooled to about 90 K with a passive radiator.

AIRS (see Figure 8) is a high-resolution grating array spectrometer covering the spectral range between 0.4 and 15.4 μm, measuring simultaneously with 2300 spectral channels using HgCdTe detectors, with a spectral resolution $\lambda/\Delta\lambda$ of 1200. This high spectral resolution enables the separation of the contribution of unwanted spectral emissions, and,

[FIGURE 8 ABOUT HERE]

in particular, provides spectral clean "super windows," which are ideal for surface observations. All channels will be downlinked on a routine operational basis. It is being built for NASA by LORAL/LIRIS in Lexington, MA.

Temperature profiles will be derived in the presence of multiple cloud layers without requiring any field-of-view to be completely clear. Humidity profiles will be derived from channels in the 6.3 μm water vapor band and the 11 Êm windows, which are sensitive to water vapor continuum. Determination of the surface temperature and surface spectral emissivity is essential for obtaining low-level water vapor distribution.

Land skin surface temperature and the corresponding IR emissivity are determined simultaneously with the retrieval of the atmospheric temperature and water profiles. Shortwave window channels are used to derive the surface temperature and corresponding spectral emissivity, and to account for reflected solar radiation. Once the surface temperature is determined, the longwave surface emissivity for the 11 Êm region can be determined, then used to retrieve the water distribution near the surface.

AIRS visible and near-IR channels between 0.4 and 1.0 μm will be used primarily to discriminate between low-level clouds and different terrain and surface coves, including snow and ice. In addition, the visible channels will allow the determination of cloud, land, and ocean surface parameters simultaneous with atmospheric corrections. Current implementation calls for four channels. One broadband channel from 0.4 to 1.0 μm will be used for the estimation of reflected shortwave radiation (i.e., albedo). Other channels will be used for surface properties such as ice and snow amount, and vegetation index.

A summary of AIRS measurement approach parameters is shown in Table 9; accomodation parameters are shown in Table 10.

[TABLES 9 and 10 ABOUT HERE]

One advanced aspect for surface imaging involved the issue of band-to-band ratios of pixels at different wavelengths. In general one deals with a spatially inhomogeneous scene, which is particularly obvious when looking down from an airplane in the winter, when there are clouds (white), land (dark and/or white), lakes (dark, unless frozen), and rivers (dark). Clearly, the pixels which are being ratioed must refer to as close to perfectly as practicable the same spot on the ground, or color uncertainties will be dominated by subtle misalignments of the pixels in the different wavelengths. The AIRS team has defined a pixel-pixel co-alignment requirement such that for all AIRS channels (about 2300 of them) the coregistration is greater than 0.99. In order to be responsive to this requirement, AIRS' design has generated an innovative focal plane.

The 3.7 to 15.4 μm spectrum is mapped by the grating into 2400 detectors, arranges in 15 linear arrays in an area of only 8 x 37mm on a sapphire substrate, cooled to 60 K. The

AIRS cooler provides the 60K temperature for the detectors, with a cooling capacity of 1.5 W. For the planned 5-year lifetime, AIRS contains two coolers for redundancy. Similar coolers of somewhat lower capacity are currently working successfully in instruments on UARS and ITSR. Passive coolers in spacecraft have been limited to 85-90 K, with a cooling capacity measured in milliwatts. These higher temperatures severely limit the detector performance. AIRS cooling technology will mean that its detectors will be essentially photon noise limited. The focal plane array technology is based largely on SDI-funded research, but extended to longer wavelengths by AIRS-specific detector development. There is only one spatial response defining aperture, which is shared by all AIRS channels. In the absence of diffraction, the coregistration between channels would equal 1, with wavelength independent optical quality. With the AIRS design concept this condition is satisfied to first order. Second order effects and diffraction, however limit this factor to 0.99 at the present time. The importance of coregistration is significant, and is recognized by NOAA, with claims that inadequate attention to coregistration is the major limitation in usability of HIRS2 and AVHRR data. While such coregistration was part of NOAA's HIRS2 specification, ITT (the instrument manufacturer) has never been able to meet it. They can attain 0.97 for some channels, but in others it is only 0.95, which is considered poor performance.

AMSU and MHS

From a surface imaging standpoint, AMSU and MHS (see Figures 9 and 10) have no primary roles, but rather serve

[FIGURES 9 and 10 ABOUT HERE]

to support surface imaging by supplying data necessary for atmospheric corrections for humidity, precipitation, temperature, etc. AMSU and MHS have a total of 20 channels: there are 15, 3.3° beamwidth channels for AMSU, and 5, 1.1° beamwidth channels for MHS. AMSU is designed primarily to obtain profiles of stratospheric temperature and to provide a cloud-filtering capability for tropospheric observations. MHS is designed to obtain profiles of atmospheric humidity and to detect precipitation under clouds with 15 km (nadir) resolution. Channels 3 to 14 on AMSU are situated on the low-frequency side of the oxygen resonance band (50-60 GHz) and are used for temperature sounding. Successive channels in this band are situated at frequencies with increasing opacity, therefore responding to radiation from increasing altitudes. Channel 1 (located on the first (weak) water vapor resonance line) is used to obtain estimates of total column water vapor in the atmosphere. Channel 2 (at 31 GHz) is used to indicate the presence of rain.

A summary of AMSU measurement approach parameters is shown in Table 11; accomodation parameters are shown in Table 12. A summary of MHS measurement approach parameters is shown in Table 13; accomodation parameters are shown in Table 14.

[TABLES 11, 12, 13, and 14 ABOUT HERE]

Channel 15 on AMSU and channel 16 on MHS are both at 89 GHz, and are also used to indicate precipitation (i.e., at 89 GHz ice more strongly scatters radiation than it absorbs or emits). Channels 17 to 20 are located on the wings of the strongly opaque water vapor resonance line at 183.3 GHz. Again, successive channels in this group have decreasing opacity; therefore, they correspond to humidities at decreasing altitudes. Channels 17 to 20, along with inputs from channel 16 and channels 1 and 2, together with the temperature profile from AIRS/AMSU/MHS, are used to obtain profiles of atmospheric humidity (i.e., water vapor).

Instrument Complementarity and Synergy

All EOS instruments have their own primary characteristics, and all fit together to complement each other. For example, as compared to MODIS, ASTER has higher spatial resolution, but lower average duty cycle (8% day, 16% night). MISR is similar to MODIS in the 250m bands. AIRS/AMSU's thermal-IR spatial resolution ranges from 15-45 km (lower than MODIS), but enable it to provide very high spectral resolution, thereby retrieving water-vapor and temperature profiles in atmosphere at high vertical resolution. AIRS will fly six moderate resolution visible channels, one of which will have a similar spectral band pass to MODIS and will permit collocation of the two data sets. MODIS data can be used for atmospheric correction for ASTER, and cloud screening for CERES. Similarly, AIRS data may be useful for MODIS atmospheric corrections, and there are synergies between MISR and MODIS in removing aerosols over oceans. ASTER, with its pointing, stereo mapping, and multispectral thermal infrared radiometer will provide synergism with MODIS and MISR, and acquire essential data for the study of volcanoes and surface climate. ASTER will provide simultaneous multi-spectral, high resolution detail to support global mapping of surface vegetation by MODIS and MISR. Simultaneous data from ASTER are essential to understand the subpixel variability of MODIS and MISR data. Figure 11 shows the spectral regions covered by the instruments discussed in this paper.

[FIG. 11 ABOUT HERE]

The synergy provided by EOS instruments may be used to:

- Archive a library of standard data products for use by the larger Earth Science community;
- Limit ambiguity in the determination of parameters through the use of multiple approaches (e.g., SST, temperature profiles, etc.);
- Obtain and apply atmospheric corrections to allow quantitative, rather than qualitative, remote sensing science; such atmospheric attenuation and cloud-screening corrections are applicable to multiple sensors, i.e., AIRS/AMSU/MHS humidity profiles for MODIS and MISR, MODIS cloud cover for CERES, MODIS total-column water vapor for ASTER, etc.;
- Validate data product algorithms and maintain instrument calibrations over a 15-year period, leading to image time series which will facilitate quantitative global change analyses;
- Derive time trajectories of multiple variables, over a given (e.g., 1 km^2) resolution,

during the growing season to derive land-cover maps;

- Provide multistage sampling;
- Support a broad range of interdisciplinary investigations describing the Earth's carbon, energy, and water cycles, and man's impact on them.

We all look forward to mid-1998, when the first of the EOS platforms reaches orbit and instrument outgassing and activation are complete. The data, created through the application of emerging technologies such as those listed above, and transported to the science community over a newly implemented comprehensive data and information system, will permit a study of the Earth as a system to a degree never before possible. The results of these studies will, in turn, be used to answer pressing science questions, and to formulate public policy for the management and mitigation, and adaptation to, global change.

Acknowledgements

We would like to thank Dr. H. H. Aumann (JPL), Dr. Frank Palluconi (JPL) and Marguerite Schier (JPL), and Dave Diner (JPL) for their information on AIRS, ASTER, and MISR, respectively. We would like to acknowledge the contributions of many people to the *1993 EOS Reference Handbook*. Dr. Nahid Khazenie, Research and Data Systems Corporation (RDC), provided critical comments on early drafts of the manuscript. Lisa Richard (RDC) provided help with graphics, and Brenda Vallette (RDC) performed layout and production of this manuscript.

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Figure Captions:

Figure 1. EOS Mission Profile

Figure 2. Moderate Resolution Imaging Spectroradiometer (MODIS) Instrument

Figure 3. MODIS Optical Path

Figure 4. MODIS Calibration

Figure 5. Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) Instrument

Figure 6. Multi-angle Imaging Spectroradiometer (MISR) Instrument

Figure 7. Multifrequency Imaging Microwave Radiometer (MIMR) Instrument

Figure 8. Atmospheric Infrared Sounder (AIRS) Single Spectrometer Configuration